THE EFFECT OF NEAR-RECEIVER SCATTERING ON SEISMOGRAMS

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ABSTRACT

In the study of physical processes involved in the generation and propagation of seismic waves at near and regional distances, it is important to distinguish those features on the seismogram which contain primary information concerning the source and those features which are due to noise. In this study the data recorded from the Non-Proliferation Experiment (NPE) are used to study the possibility that signal generated noise caused by scattering of elastic waves near the receiver may contribute significantly to the recorded waveforms of the direct P wave. Two different examples of anomalous waveforms, the vertical component of free-field recordings and the transverse component of surface recordings are investigated.

The results of this study indicate that elastic wave scattering near seismic receivers can have a significant effect upon recorded waveforms, with effects as large as 50% of the primary wave easily achieved. The scattering effect is complex, with strong directional, frequency, and near-field effects. A better understanding of these scattering effects could lead to improved methods of siting seismic receivers for the purposes of reducing the signal-generated noise on seismograms.

OBJECTIVE

The general objective of this research effort is the detection and discrimination of underground explosions through the study of radiated seismic waves. Particular emphasis is on the study of physical processes in the source region through the development of improved models for the generation and propagation of elastic waves. Such models are tested by the collection and analysis of broad-band seismic data at near and regional distances. The present paper reports on one phase of the research effort which is concerned with the reliability of source parameters which are inferred from the analysis of waveform data. The near-source seismic data from the Non Proliferation Experiment (NPE) provide an opportunity to check one aspect of this general problem.

RESEARCH ACCOMPLISHED

Introduction

The ability to extract useful information about seismic sources from seismic waveform data is limited by the amplitude and characteristics of the noise present on the seismograms. A type of noise which is particularly treacherous in this respect is that which is signal generated, as it typically has the transient character and frequency content which can easily be mis-interpreted as due to some property of the source.

This study is concerned with the signal generated noise which is contributed by scattering of elastic waves near the receiver. Such scattering will occur whenever the waves encounter lateral heterogeneity in earth properties, and, unfortunately, the shallow crust of the earth where most seismic receivers are located is a region of strong heterogeneity. The question to be investigated is whether the amplitude and frequency content of these scattered waves are sufficient to represent a significant source of noise on the seismograms used to study seismic sources.

Characteristics of seismic scattering

The existence of scattered energy on seismograms is well established and provides evidence of earth heterogeneity on a broad range of length scales. The codas on seismograms are the most obvious examples of scattering and also the most commonly analyzed effects of scattering. However, it is apparent that energy represented by codas was originally derived from primary waves, and thus these primary waves must also be affected by the scattering. The present study is primarily concerned with the effects of scattering upon these primary waves.

While the effects of scattering are typically analyzed by treating the scattering as a stochastic process, the objectives of the present study require a more deterministic approach. This causes a considerable increase in the difficulty of the analysis, as several different types of effects have to be considered simultaneously. These effects are discussed in considerable detail in the papers by Korneev and Johnson (1993a, 1993b), and Gritto et al. (1995), so they will only be briefly summarized here. The strong directional effects of scattering are usually illustrated by scattering diagrams, which show, depending upon frequency, various combinations of forward scattering, backward scattering, and scattering at oblique angles. The strong frequency dependence of scattering is usually illustrated by scattering cross-sections and can be classified in terms of ranges where Rayleigh, Mie, and ray scattering are dominant. Scattering is a very efficient method of converting wave types, with P to S conversions generally stronger than S to P conversions. Finally, it is important to recognize that scatterers can be viewed as secondary sources in the sense that they have different radiation patterns and different distance dependencies for far-field and near-field parts of the scattered field.

In the analysis of scattering effects there is a choice between using exact solutions for approximate geometries and using approximate solutions for more realistic geometries. The first choice has been selected in the present study, where the canonical problem of scattering from a spherical inclusion is used to illustrate some of the effects of scattering. It is important to point

out that the objective of the study is not to solve an inverse problem for the determination of the location and strength of the heterogeneities causing the scattering, as the amount of available data are insufficient for this purpose. Rather, the intent is to investigate whether the scattering effects of credible heterogeneities are consistent with some of the anomalous effects observed on seismograms.

Source of data

The Non-Proliferation Experiment (NPE) provided an excellent data set with which to test some of the critical issues concerning the effects of near-receiver scattering. This experiment consisted of detonating 1.1 kt of chemical explosive at a depth of 389 meters within Rainier Mesa at the Nevada Test Site in September of 1993. The resulting ground motions were well recorded by a large number of instruments, including free-field gauges in the distance range of 100 to 1100 meters at shot level and surface gauges at epicentral distances of 600 to 2200 meters. The data analyzed in this study came from several different sources, including the Lawrence Livermore National Laboratory, the Los Alamos National Laboratory, Southern Methodist University, the Lawrence Berkeley National Laboratory, the University of California at Berkeley, and the Defense Nuclear Agency.

The fact that the NPE was a very well-controlled experiment which produced large amounts of high-quality seismic data provides an opportunity to isolate some of the scattering effects. Good estimates of both the source function and the velocity structure of the surrounding region are available, making it possible to model most of the primary features that were recorded on the seismograms. However, there are a few features of the seismograms which are not easily explained by simple source and propagation effects, and it is these features which have been investigated in terms of their possible scattering origin.

Analysis of free-field data

Figure 1 shows part of the tunnel complex which was used to emplace and record the NPE explosion. The tunnels are horse-shoe shaped and the larger ones have a nominal diameter of about 6 meters. Free-field recordings of ground motion were obtained with three-component accelerometers grouted into small drilled holes at about 1 tunnel diameter below the tunnel floor. Given the facts that the geological layers are approximately horizontal and relatively homogeneous (Baldwin et al., 1994) and that major discontinuities such as the free surface and basement are some distance away, it would appear that these instruments should produce accurate recordings of the free-field displacements caused by the explosion. However, it remains to be determined whether elastic waves scattered from the tunnel could have a significant effect upon the recorded seismograms.

Figure 2 illustrates the three components of ground motion recorded at station TM07 at a horizontal distance of 228 meters and about 5 meters below the center of the NPE explosion. Based solely upon this geometry, one would expect the ground motion to be almost entirely radial, which is clearly not the case. This study has concentrated upon explaining the anomalous motion on the vertical component, which for station TM07 is about 37% of the radial motion. Two possible explanations have been considered, one being the refraction of the direct P wave by a velocity gradient near the depth of the explosion, and the other being the scattering of the direct P wave by the tunnel.

The proper method of modeling the tunnel complex shown in Figure 1 for the purposes of the scattering calculations is not obvious. Station TM07 was chosen for analysis primarily because the relationship between the source, receiver, and tunnel complex appeared to be the most simple for this station. However, even in this case it is clear that a single infinite cylinder is not a good approximation to the situation at station TM07. Instead, the tunnels near station TM07 have been modeled by summing the effects of a series of overlapping spheres, with 13 different spheres

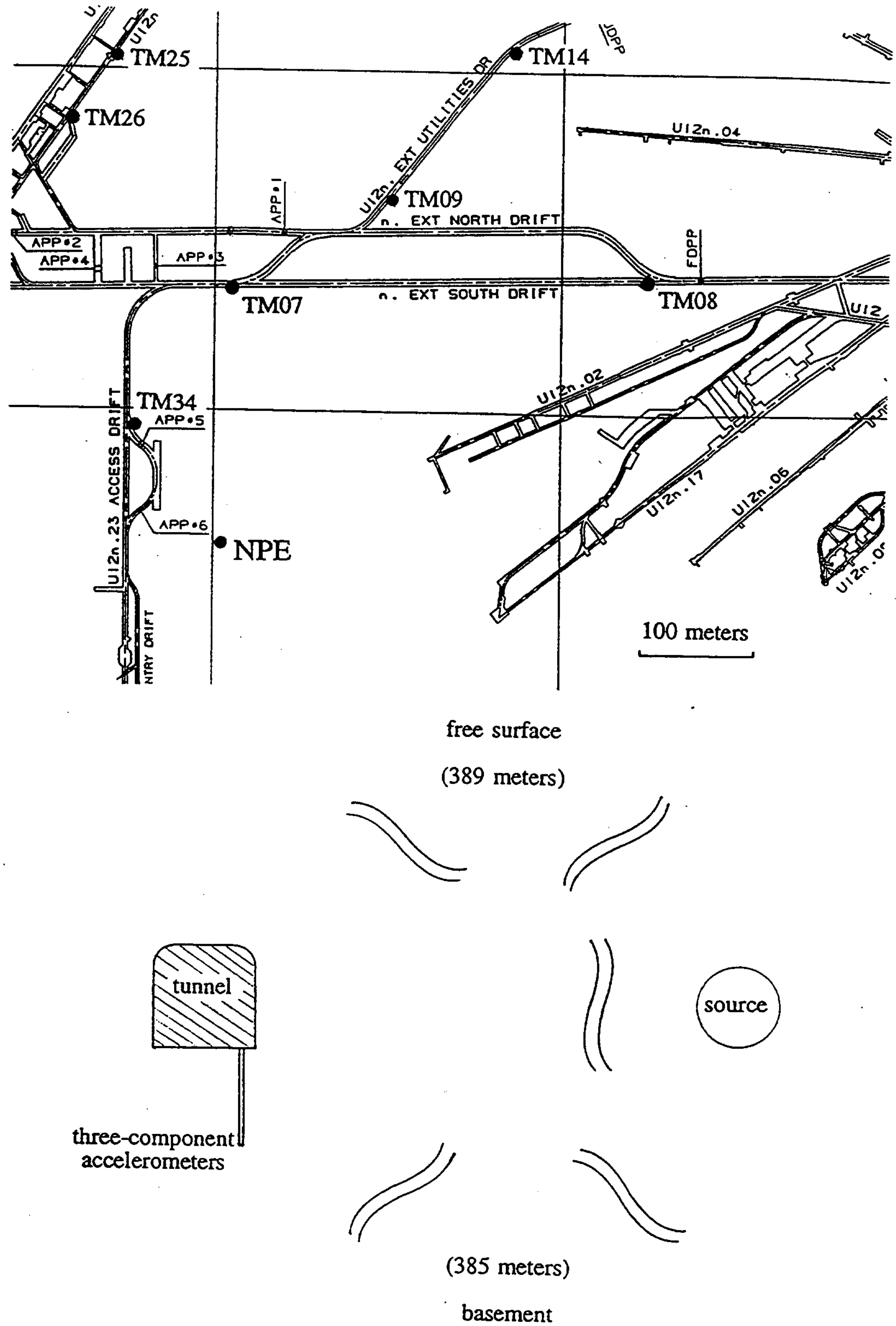


Figure 1. The emplacement geometry for the free-field part of the NPE experiment. The upper part of the figure shows the tunnel complex at a depth of about 390 meters in the vicinity of the NPE explosion. The lower part is a sketch of how the gauges were placed in holes drilled from the bottom of the tunnels.

used to model the three tunnel elements within about 20 meters of the station. With this approximation it is assumed that more distant parts of the tunnel complex do not have a significant effect and that multiple scattering between the spheres is not important. Some preliminary numerical calculations indicated that these approximations are reasonable, but more work on this aspect of the problem is definitely required.

The middle and lower parts of Figure 2 show the comparison between the observed and calculated seismograms for station TM07. The traces labeled "structure" were obtained by assuming a model for velocity structure that had a positive velocity gradient of approximately 4 km/sec/km for the P velocity in the depth range of the explosion. While this is a strong velocity gradient, it is not completely inconsistent with the available information concerning the geological structure of Pahute Mesa. The traces labeled "scattering" were obtained by only considering the scattering effects of the tunnel complex, as outlined in the previous paragraph. The structure and scattering calculations both produce results for an impulse source and thus must be convolved with a source time function in order to compare with the observational data. Here it was assumed that the radial component of motion was a reasonable approximation to the free field motion, and so the time function on this component was used as the source time function. Thus the agreement in Figure 2 for the radial accelerations is to be expected, although the structure calculations do not agree as well as do the scattering calculations. The results for the vertical accelerations in Figure 2 are the primary interest, as they illustrate that both structure and scattering have the potential to explain an appreciable amount of the anomalous motion on this component, with the maximum being 46% of the observed for the structure and 80% for the scattering. As far as agreement in waveforms, the structure result appears to have a generally lower frequency content than the observed, while the scattering result has somewhat higher frequencies.

Figure 3 illustrates another method of investigating the relative contributions of structure and scattering. The ratio of vertical to radial components in the frequency domain for the structure calculations is larger at low frequencies and smaller at high frequencies than the observed ratio. This ratio for the scattering calculations agrees quite well with the general trend of an increase with frequency which is contained in the observed data, providing strong evidence that scattering effects are a significant part of the anomalous motion observed on the vertical component.

The results in Figure 3 show that the scattering effect of the tunnel can be significant for instruments that are emplaced only one tunnel diameter away from the tunnel. It is worth noting that if the effective size of the tunnel were actually greater than that used in the scattering calculations, then the amplitude of the scattered wave on the vertical component would be increased and its frequency content decreased, producing a better agreement with the observations. This could possibly be due to the fact that the total lengths of the tunnels were not completely modeled or that the excavation of the tunnel has caused a change in material properties in its immediate vicinity. It is should also be noted that the most likely explanation is a combination of structure and scattering effects, but this is a much more complicated calculation because scattering effects have to be calculated for a variety of waves arriving at the recording site.

Analysis of surface data

Another example of features on seismograms which are not easily explained by simple source and propagation effects was produced by recordings of the NPE at the surface. Figure 4 shows the radial and transverse components of ground acceleration which were observed at a north-south linear array which was located about 600 meters west of the NPE epicenter. The spacing between the recording sites was about 100 meters. The instruments were buried in soil about 0.3 meters below the surface of Rainier Mesa. The vertical component is not shown here, but its general appearance is very similar to the vertical with slightly smaller amplitudes, indicating waves arriving at an angle of about 45 degrees with respect to the surface normal. The radial accelerations in Figure 4 show a general similarity across the array for the initial waveform, as

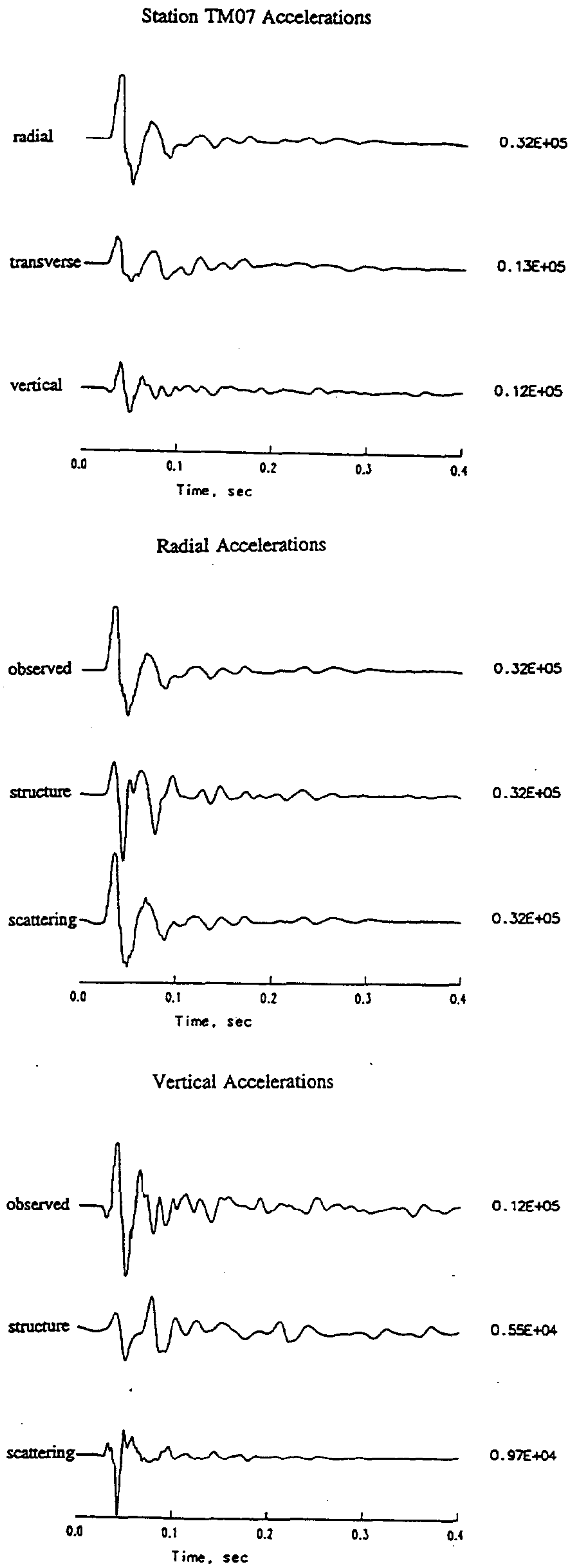
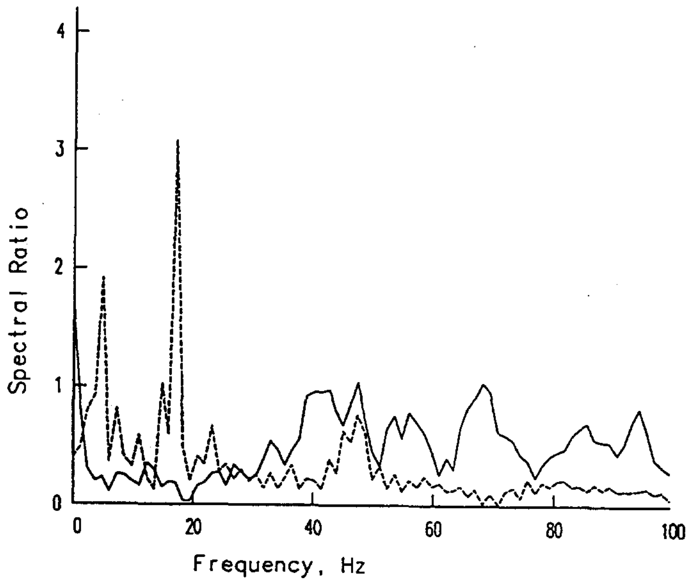


Figure 2. The results of the analysis for the free-field data recorded at station TM07 at a distance of 228 meters from the NPE explosion. The top panel shows the observed accelerations, with the numbers on the right being maximum accelerations in units of cm/sec^2. The middle and bottom panels show a comparison between observed and calculated accelerations for the radial and vertical components, with the structure calculation representing the effects of a velocity gradient in the vicinity of the explosion and the scattering calculation representing the effects of scattering from the tunnel.



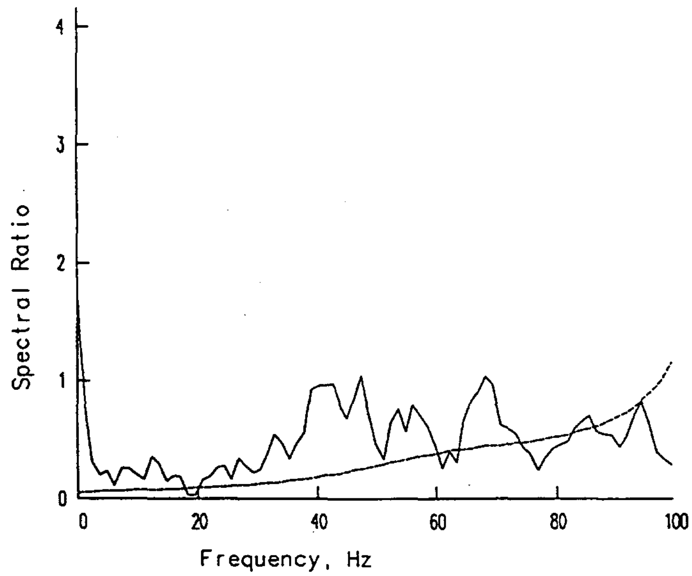


Figure 3. Spectral ratios of the vertical to radial components for the free-field station TM07. In both the upper and lower parts the solid line is for the observed data, while the dashed line is the calculated ratio for the effects of structure in the upper part and for the effects of scattering from the tunnel in the lower part.

one would expect for these closely spaced recording sites. However, the transverse components of acceleration are rather anomalous, as there should be no high-frequency transverse components of motion arriving with the P velocity from an explosive source. Also note that these transverse motions can change considerably over distances of 100 meters, which is quite different from the situation with the radial and vertical components.

The upper part of Figure 5 shows the three components of acceleration recorded at station UCB120. The maximum acceleration on the transverse component is 60% of that on the radial component and the frequency component on the transverse component appears to be significantly higher than on the other components. This higher frequency content is suggestive of a scattering origin, so the possibility that the motion on this transverse component was due to scattering was investigated. The fact that the motion on the transverse component begins simultaneously with that on the radial and vertical components suggests that the scattering object must be near the receiver. However, the precise location and properties of the scattering object or objects can not be determined with the available data, so only calculations for plausible situations are possible. The surface of Rainier Mesa is a relatively flat tuff unit partially covered by weathered rock and soil. It was hypothesized that the scattering was caused by an interface between rock and soil and modeled by a spherical boulder of unweathered rock 30 meters in radius surrounded by soil. While a spherical boulder was used for the calculations, this could also be considered as an approximation to an uneven boundary between weathered and unweathered material or to a topographic protrusion of unweathered material. Free surface effects were not included in these calculations.

The middle and lower parts of Figure 5 show the results of such scattering calculations for station UCB120 with the boulder placed 26 meters from the station. As with the free-field calculations, the waveform on the radial component was used as the source time function to be convolved with the results of the scattering calculations. The maximum amplitude on the transverse component for this scattering calculation is about 50% that which was observed, but the frequency content and general appearance of the records is quite similar. The amplitude of the scattered wave on the transverse component is somewhat arbitrary, as it depends strongly upon the distance to the scatterer. This is illustrated by similar calculations that were were performed for station UCB140, which has its observed waveforms displayed in Figure 6. The scattering calculations are shown in the middle and lower parts of Figure 6, where the scatterer is now located only 10 meters away from the station. The maximum amplitude on the transverse component contributed by the scattering is now even larger than observed, with the same good agreement with respect to waveforms and frequency content that was noted in Figure 5. It should be pointed out these results were obtained for a single scatterer, whereas a more realistic situation would be a number of scatterers having different properties and located at different distances. While these calculations were performed for a geometry which is likely to be a gross over-simplification of the actual situation that exists on Rainier Mesa, it seems clear that scattering of elastic waves near the receiver is capable of explaining the anomalous arrivals on the transverse component which arrive at the time of the direct P wave.

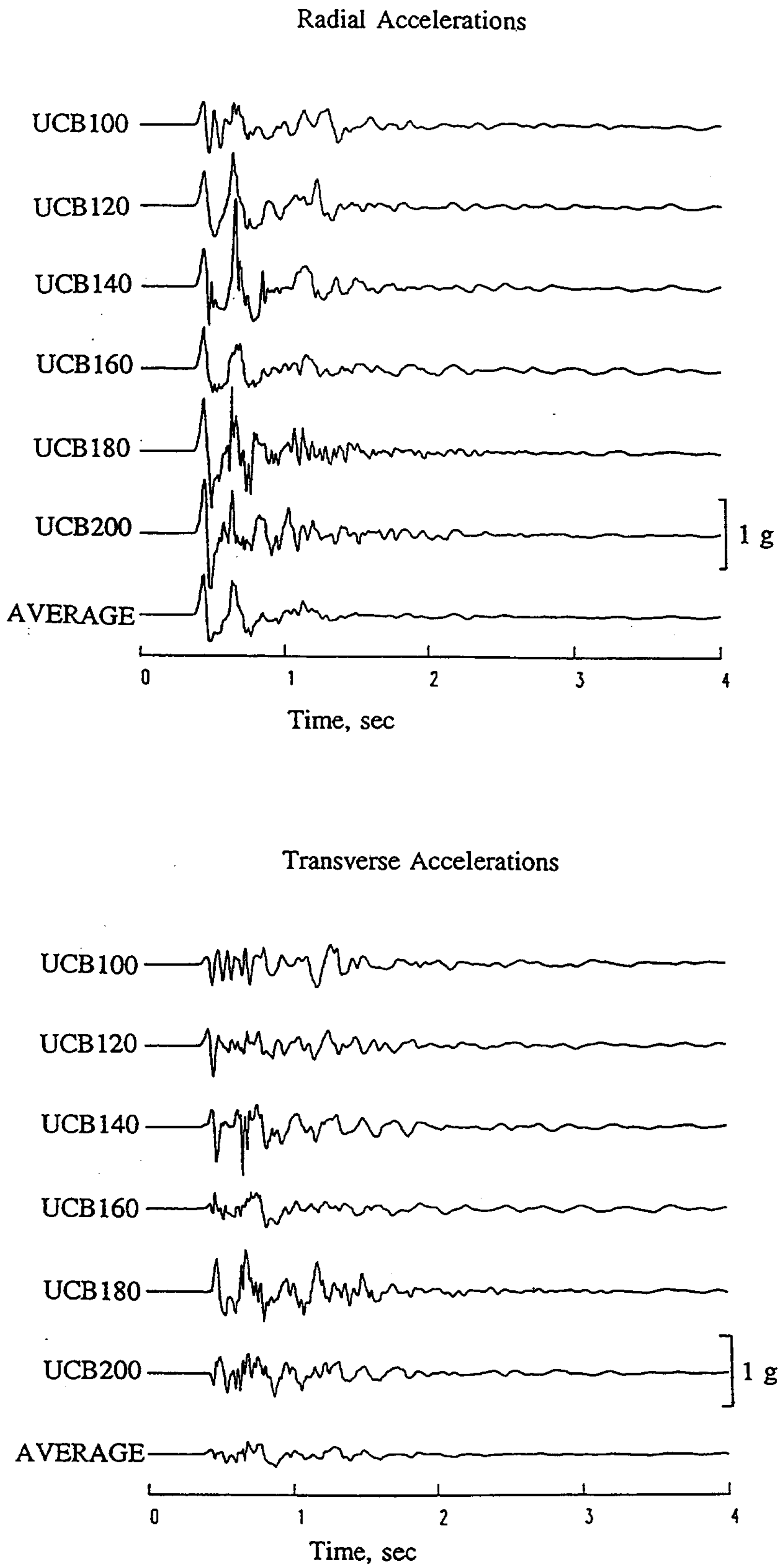


Figure 4. Accelerations recorded on the surface of Rainier Mesa from the NPE explosion on a linear north-south array located about 600 meters west of the epicenter.

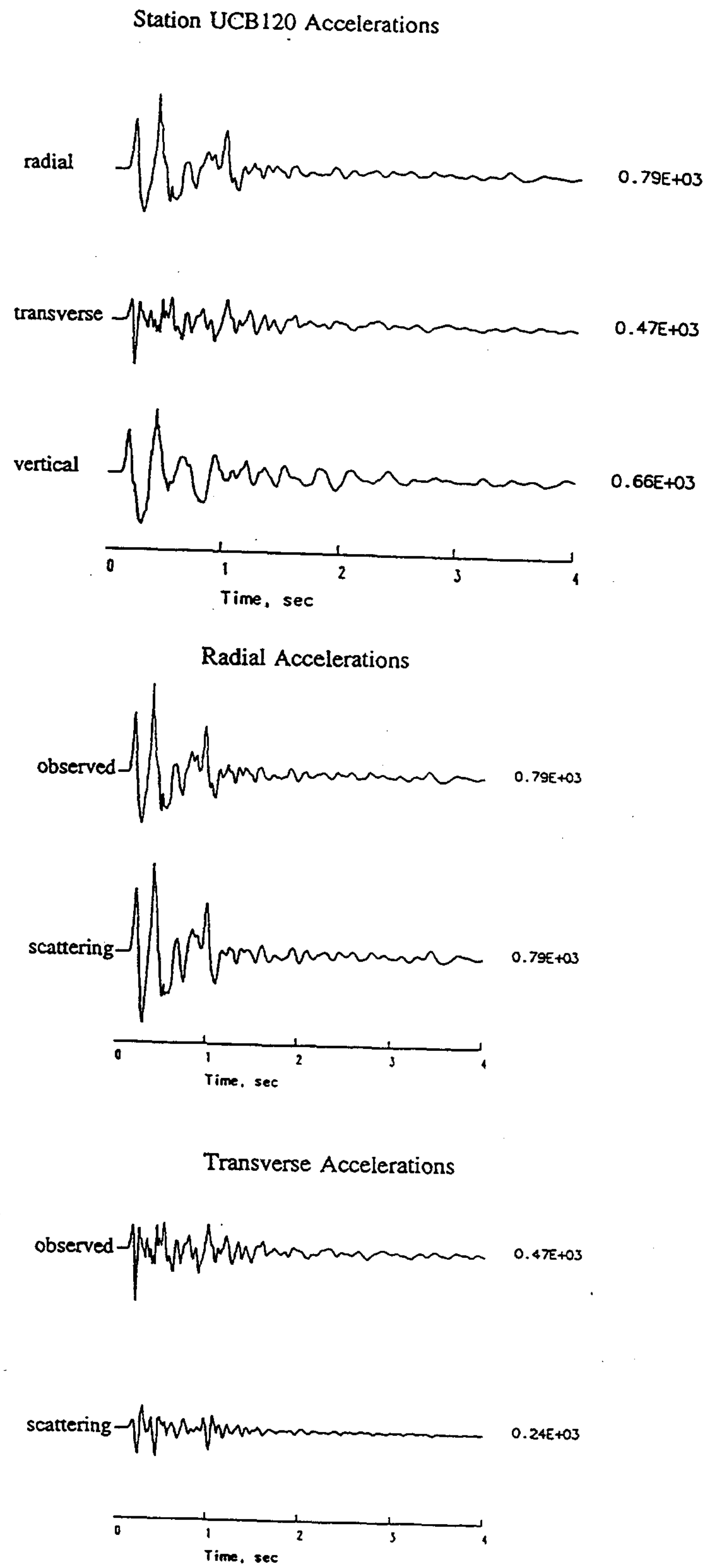


Figure 5. The results of the analysis for the surface data recorded at station UCB120 at an epicentral distance of 662 meters from the NPE explosion. The top panel shows the observed accelerations, with the numbers on the right being maximum accelerations in units of cm/sec^2. The middle and bottom panels show a comparison between observed and calculated accelerations for the radial and transverse components. In this case the scattering is from a high-velocity obstacle 30 meters in radius located 26 meters from the station.

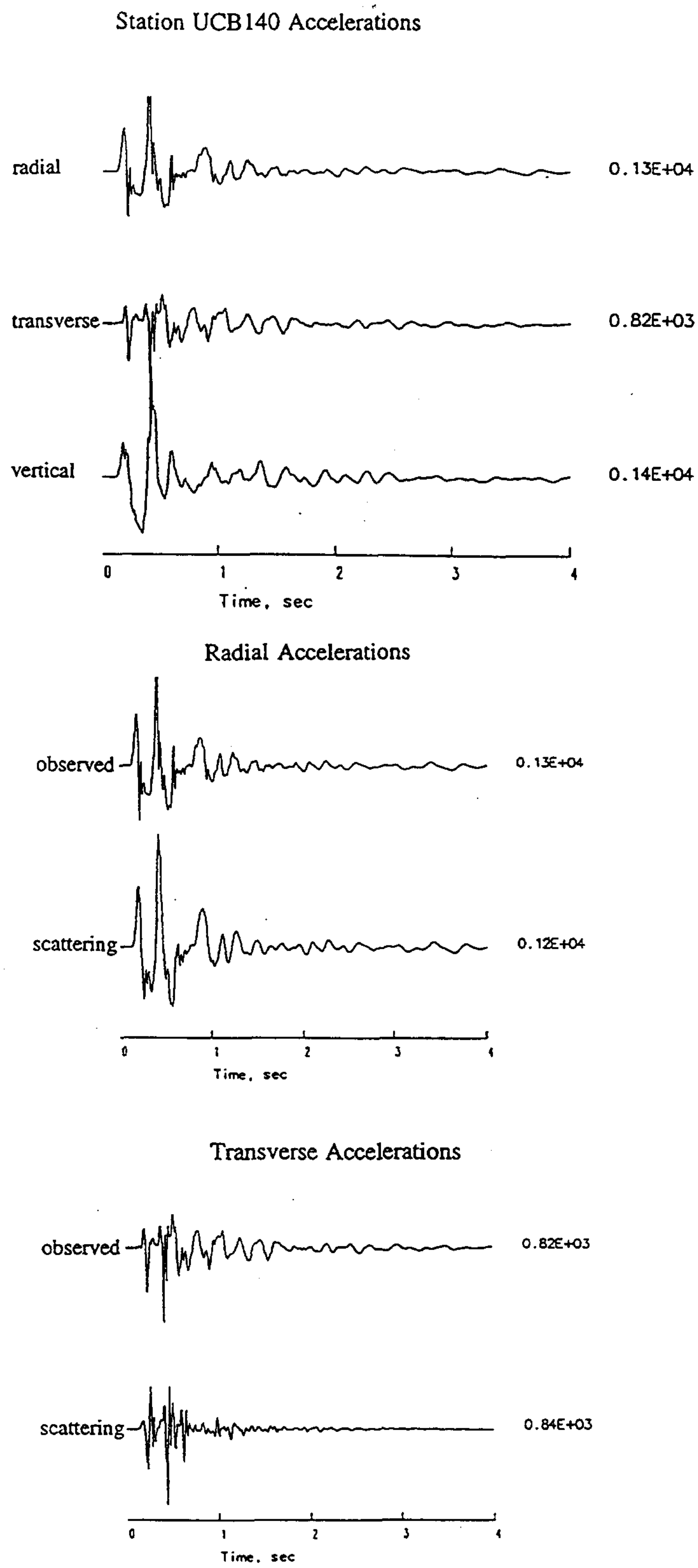


Figure 6. The results of the analysis for the surface data recorded at station UCB140 at an epicentral distance of 596 meters from the NPE explosion. The top panel shows the observed accelerations, with the numbers on the right being maximum accelerations in units of cm/sec^2. The middle and bottom panels show a comparison between observed and calculated accelerations for the radial and transverse components. In this case the scattering is from a high-velocity obstacle 30 meters in radius located 10 meters from the station.

CONCLUSIONS AND RECOMMENDATIONS

The seismic data provided by the NPE have allowed an investigation of some features of the seismic data which are somewhat anomalous and difficult to explain with simple source and propagation effects. The investigation of scattering as a possible cause of these features has led to the following preliminary conclusions:

- Elastic wave scattering near seismic receivers can have a significant effect upon recorded waveforms.
- Scatterers act as secondary sources, with near-field terms and strong directional effects.
- Scattering is effective in changing the wave type and direction of particle motion, so it often causes anomalous components of motion.
- Scattering effects tend to increase with frequency, which may serve as a diagnostic tool.
- Scattering effects are enhanced in low velocity materials, so near surface regions are especially prone to this phenomenon.

A better understanding of some of the possible effects of scattering may lead to methods of mitigating such effects, and this lead to the following general recommendation.

- The consideration of scattering effects in the siting of seismic receivers could help reduce the signal-generated noise on seismograms.

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